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LETTER TO THE EDITOR

Note on the quasimolecular M radiation in very heavy collision systems†

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Abstract. The quasimolecular M radiation emitted in collisions between Xe ions of up to 6 MeV energy and solid targets of Ta, Au, Pb and Bi, as well as a gaseous target of $Pb(CH_3)_4$, has been studied. Using a realistic theoretical correlation diagram, a semi-quantitative explanation of the observed peak structure is given.

In collisions between energetic ions, non-characteristic x-rays have been found which were interpreted as radiative transitions between states in the molecule transiently formed during the collision ('MO x-rays'). Generally, after correction for absorber effects they appear as a tail at the high-energy side of characteristic lines. As one exception, the molecular M radiation in collision systems such as I–Au at ion energies between approximately 6 and 10 MeV was found to form a broad peak around 8 keV even after correction for absorber effects (Mokler *et al* 1975).

In this letter we report on the observation of the MO radiation in such heavy collision systems below 6 MeV ion energy. Collimated beams of Xe ions from the SUNI 6 MV Van de Graaff were injected into thin Ta, Au, Pb and Bi targets; for gaseous targets, $Pb(CH_3)_4$ vapour from 50% $Pb(CH_3)_4$–xylene as well as 60% $Pb(CH_3)_4$–toluene mixtures was used. The x-rays emitted were detected through a 29 μm Al absorber in a 28 mm^2 Si(Li) detector placed perpendicular to the beam axis. Figure 1 shows the energy dependence of x-ray spectra for the Xe–Au case. The broad structure between 6 and 11 keV shows a pronounced peak at about the united-atom M x-ray energy in the entire ion energy range investigated. The peak structure persists when the Al absorber is taken into account. Similar behaviour is found for the other collision systems investigated (figure 2). The energy threshold for excitation of the x-ray structure between 6·5 and 11 keV lies between about 1·5 and 2·5 MeV (figure 3); the total cross sections were evaluated neglecting any anisotropy in the x-ray emission, but taking into account energy loss in the solid targets. Our Xe–Au data are in good agreement with those of Mokler *et al* (1975) for the I–Au system.

In earlier studies (Lutz *et al* 1972), a steady-state M excitation was found for such heavy ions penetrating solid targets due to the high collision frequency. Similarly, a steady state L excitation was postulated by Mokler *et al* (1975) to explain the appearance of the MO structure in collisions between I ions and heavy atoms.

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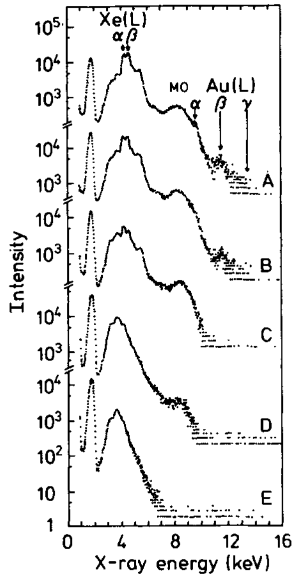

Figure 1. Spectra of x-rays excited in Xe–Au collisions (not corrected for the 29 μm Al absorber). Collision energies: A, 5·5 MeV; B, 4·0 MeV; C, 3·0 MeV; D, 2·0 MeV; E, 1·5 MeV.

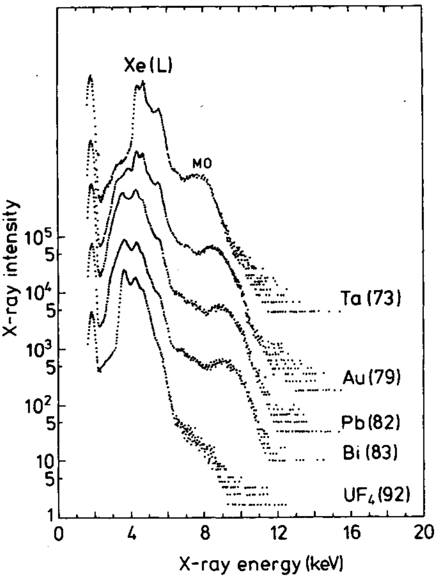

Figure 2. Spectra of x-rays excited in the collision systems 3·5 MeV Xe on Ta, Au, Pb, Bi and UF$_4$ (not corrected for the 29 μm Al absorber).

The similarity in the energy thresholds for Xe$_L$ and MO x-ray excitation found in our solid target measurements would seem to offer supporting evidence for this multi-collision postulate. However, we also found appreciable MO radiation in a dilute gas target; for 4 and 5 MeV Xe on Pb(CH$_3$)$_4$, at least 50% of the MO yield found in solid Pb is still present if the yield spectra are normalized to each other at the

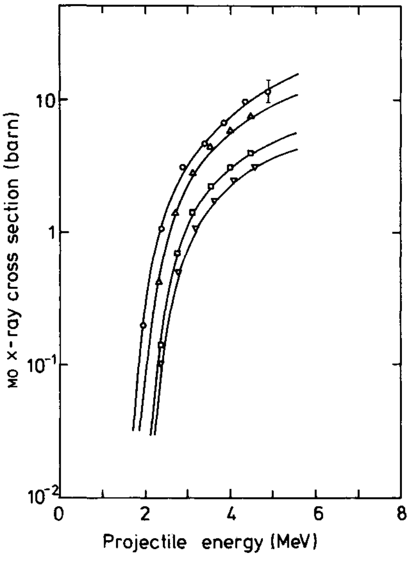

Figure 3. Total cross section of 6·5–11 keV MO x-ray excitation in collisions between Xe projectiles and Ta (○), Au (△), Pb (□) and Bi (▽) (corrected for ion energy loss in the targets).

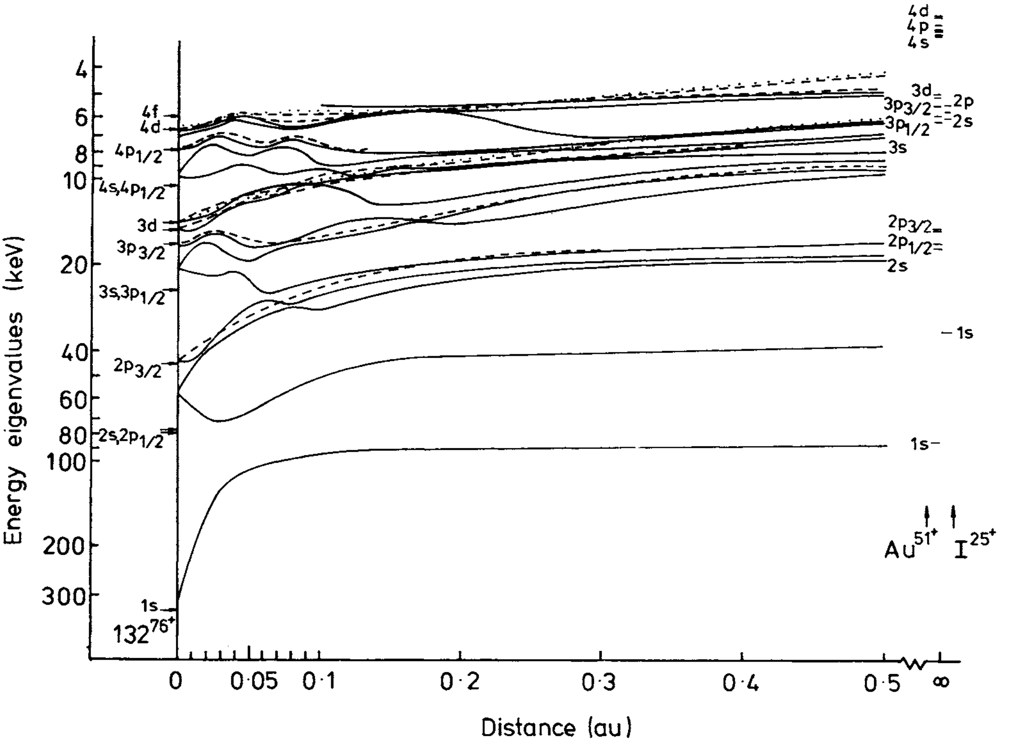

Figure 4. Relativistic correlation diagram for the I–Au system (56 electrons).

Xe_L energy (the spectra are very much alike for the solid and gaseous targets, and the measured Xe_L cross sections are, within 30% experimental uncertainty, in quantitative agreement). Thus, vacancies must be transferred into the molecular M levels in one collision as well, i.e. vacancy sharing processes between close-lying molecular levels could play a significant role in the quasimolecular M excitation in such systems. This may also be inferred from a quantitative correlation diagram of the I–Au system (figure 4): a large number of molecular levels merging into the I_N, I_M, Au_M and I_L shells run nearly parallel over a wide range of internuclear distances, adjacent ones being separated only by small energy gaps of the order of a few hundred eV. A fairly wide energy gap of about 5 keV exists between the molecular levels merging respectively into the I_L and the Au_L shells. As a result, vacancy transfer into the Au_L shell will occur with appreciable probability only at the crossing at an internuclear distance $R \simeq 0{\cdot}05$ au. The corresponding minimum ion energy is approximately 4 MeV, in agreement with the observed Au_L excitation threshold.

The I–Au correlation diagram (Rosén *et al* 1976) also allows a semi-quantitative explanation of the peak structure at about 8 keV x-ray energy. In the quasistatic approximation, the cross section $d\sigma/dE_x$ for spontaneous emission of an MO photon disappears for x-ray energies E_x corresponding to a separation $R = b$ (b is the distance of closest approach in a head-on collision); it increases approximately as R^2 for larger R (Briggs 1974). Peaks appear at x-ray energies for which dE_x/dR is small. The peak intensity will be higher for smaller level curvature, and (because of the R^2 dependence) for larger internuclear distance R at which the transition occurs. For example, the I–Au correlation diagram gives a rather flat region in the 4d–$3p_{3/2}$

transition between $R \simeq 0{\cdot}12$ and 0·18 au with $E_x = 7{\cdot}5$–8 keV. There is another flat region in this transition at $R \simeq 0{\cdot}06$ au with E_x between 10 and 11 keV; the corresponding x-ray peak, however, is much more difficult to observe. At ion energies below 3 MeV, the ions do not penetrate deeply enough ($b > 0{\cdot}07$ au); at higher ion energies, the R^2 dependence of $d\sigma/dE_x$ strongly favours the 8 keV peak, and the target L radiation obscures the higher-energy transitions. There are other transitions showing regions of $dE_x/dR \simeq 0$. In general, those regions appear either at smaller R, or the corresponding x-ray energy $E_x < 8$ keV. Therefore, an appreciable MO contribution to the x-ray spectrum should lie underneath the characteristic $\mathrm{Xe_L}$ lines. Other transitions may contribute to the MO peak as well, e.g. from continuum states into molecular states having binding energies of about 8 keV. Such contributions are expected to show an energy dependence similar to that found for radiative electron capture (cf Bethe and Salpeter 1957) and should thus be experimentally distinguishable from transitions between inner molecular levels.

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